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16. ABSTRACT

Acid rain occurs in the midwest. Studies to date have suggested minimal yield response of field corn to acid rain. However, small but significant reductions in yield have been shown for some cultivars under extreme conditions. To define further these yield changes this study examined the effect of simulated acid rain on parameters associated with corn yield. Cultivars `B73 x Mo17' and `Pioneer 3377' were shielded from ambient rain by two movable rain exclusion shelters. Six simulated rain treatments were applied biweekly within these shelters through the use of a nozzle distribution system. For the most part growth and yield parameters were unaffected by simulated rain treatment. Analysis of 2 years of data for 100-seed dry weight, dry matter production, cob weight, barren plants and seed protein content indicated no significant trends with treatment pH for either cultivar. However, when contrasted with all other treatments a small yield reduction observed at pH 3.0 for B73 x Mo17 was associated with a similar reduction in ears, cob dry weight, kernels per ear, and slightly increased seed protein. Thus, while the only significant yield reduction was a contrast of pH 3.0 and the average of all other treatments for B73 x Mo17, this reduction appears to be the result both of slightly fewer ears and slightly less successful ear fill.

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GROWTH PARAMETER AND YIELD COMPONENT RESPONSE OF FIELD CORN TO SIMULATED ACID RAIN

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BANWART W. L., PORTER P. M., ZIEGLER E. L. and HASSETT J. J. Growth parameter and yield component response of field corn to simulated acid rain. ENVIRONMENTAL AND EXPERIMENTAL Botany **28,** 43–51, 1988.—Acid rain occurs in the midwest including major portions of the Corn Belt. Studies to date have suggested minimal yield response of field corn (*Zea mays* L.) to acid rain. However, small but significant reductions in yield have been shown for some cultivars under extreme conditions. To define further these yield changes this study examined the effect of simulated acid rain on parameters associated with corn yield. Cultivars 'B73 × Mo17' and 'Pioneer 3377' were shielded from ambient rain by two movable rain exclusion shelters. Six simulated rain treatments (pH 5.6, 4.6, 4.2, 3.8, 3.4, 3.0) were applied biweekly within these shelters through the use of a nozzle distribution system. For the most part growth and yield parameters were unaffected by simulated rain treatment. Analysis of 2 years of data for 100-seed dry weight, dry matter production, cob weight, barren plants and seed protein content indicated no significant trends ($\alpha \leqslant 0.05$) with treatment pH for either cultivar. However, when contrasted with all other treatments, a small yield reduction ($\alpha \leqslant 0.05$) observed at pH 3.0 for B73 × Mo17 (6%) was associated with a similar reduction in ears (5%), cob dry weight (5%), kernels per ear (3%) and slightly increased (3%) seed protein. Thus, while the only significant yield reduction was a contrast of pH 3.0 and the average of all other treatments for B73 × Mo17, this reduction appears to be the result both of slightly fewer ears and slightly less successful ear fill.

INTRODUCTION

ACID rain is a documented phenomenon over much of the eastern and midwestern U.S.A. including major portions of the Corn Belt. The mean annual pH of rainfall in east central Illinois where these studies were conducted is approximately 4.3. The value of field and sweet corn grown in the U.S.A. has exceeded $20 billion dollars in recent years.[11] There have been relatively few studies on the response of corn (*Zea mays* L.) to simulated acid rain, especially those that examine the entire plant development.

In 1979 the sweet corn cultivar 'Golden midget' was subjected to simulated acid rain and harvested before physiological maturity.[3,9] No data on grain yield were obtained but leaf injury (necrotic spots on the leaves) resulting from simulated rain at pH 3.0 was noted at harvest. The estimated fraction of the leaf area affected was 5% at this pH, while no apparent injury to leaves occurred at pH treatments 3.5, 4.0 and 5.6. Although foliage at pH 3.0 exhibited visible injury, total aboveground dry weight (stems and leaves) of these plants was larger by 13% than plants receiving the pH 5.6 treatment. No significant effect of simulated acid rain on roots was observed.

The effect of simulated acid rain on dent corn ('Pioneer 3992') was studied by LEE and coworkers.[6,7,8] The lowest yield was observed at pH 4.0 in both years, but only in 1980 was the difference in grain yield between the pH 4.0 treatment and the control treatment (pH 5.6) sig-

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nificantly different. No significant differences in yield were noted between the control treatment and the pH 3.5 and 3.0 treatments. Depressed yields at pH 4.0 appeared to be due to a decrease in the number of two-eared plants in 1980, but not in 1981. However, stover production in 1981 was significantly reduced at the pH 4.0 treatment when compared to the control.

Total ear fresh weight, ear dry weight, grain dry weight and top dry weight for two early maturing cultivars, Pioneer 3992 and 'Northrup King PX39', were not significantly affected by simulated acid rain treatments at pH 3.5, 3.7, 3.9, 4.1, 4.3 and 5.4.[10] In additional experiments with Pioneer 3992, grain yield was not significantly affected by pH 4.0 simulated acid rain treatments of differing nitric : sulfuric acid ratios.[10] Similarly grain yields were not affected when simulated rain varied from event to event with the same season-long average. PLOCHER *et al.*[10] suggest that corn can be particularly sensitive to acid precipitation under some conditions, and that field tests are needed to evaluate the response of corn to controlled applications of simulated acid rain.[10]

Work by DUBAY and co-workers (personal communication, North Carolina State University) involved the development of greenhouse techniques to test 10 corn cultivars for relative sensitivity to simulated acid rain. Young plants were exposed for 1 hr to simulated rain at pH 5.5 or 2.5, then ranked for visible foliar injury. There was never greater than 5% foliar injury (percent of leaf surface brown or necrotic) to any of the cultivars receiving the most acidic treatment.

The buffering ability of corn (*Zea mays* rugosa, 'Butter and Sugar') leaf tissue was evaluated by placing sections of leaves in a simulated sulfuric acid rain solution.[4] The corn leaf tissue had little effect on the pH of the acid rain solution over the 4 hr time period that pH was monitored.

WALDRON *et al.*[12] investigated the susceptibility of the reproductive process in three corn cultivars to simulated acid rain. Their study focused on pollen viability and growth, as well as silk receptivity and kernel formation. Preliminary observations indicated that in one corn cultivar there was a reduced kernel number on ears where the silks and tassels were treated with simulated acid rain at pH 3.6 and that simulated acid rain may decrease pollen germination.

The primary objective of this study was to elicit more detailed information on responses of growth parameters and yield component responses of two corn cultivars to different acidity levels of simulated rain. The study was conducted in an area where corn is a major crop and where acid precipitation occurs naturally. The pH of rainfall in the geographic region of this study varies from as low as 3.0 to values as high as 7.0 with the mean annual pH of approximately 4.3 (personal communication, Illinois State Water Survey, 2204 Griffith Dr., Champaign, IL 61820). In an earlier paper the grain yield response of two corn cultivars to six levels of simulated acid rain ranging from pH 3.0 to 5.6 applied biweekly from planting to physiological maturity was reported.[1] To assess the effects of acidic precipitation on corn or other cropping systems it is important not only to examine yield but yield components and other plant parameters that may provide some evidence for the mechanism involved in acid rain effects. In this paper the growth parameters and yield component responses associated with the simulated rain acidity levels are reported.

MATERIALS AND METHODS

Field studies were conducted in 1983 and 1984 on a Flanagan silt loam (fine, montmorillonitic, mesic Aquic Argiudoll) using dent corn 'B73 × Mo17' (Illinois Foundation Seeds, Inc., Champaign, IL) and 'Pioneer 3377' (Pioneer Hy-Bred International, Princeton, IL). B73 × Mo17 was selected because of its relative sensitivity to drought stress and Pioneer 3377 because it is a high yielding commercial cultivar. The detailed experimental design, procedures and data analysis methods that were employed in this experiment were given in detail by BANWART *et al.*[1]

The statistical design consisted of a split plot with the main plot arranged in a randomized complete block design. The main plot and split plot variables were six simulated rain acidity levels and two cultivars, respectively. Plants were protected from ambient rain by movable rain exclusion shelters.[1] Corn was treated biweekly with 1.05 cm of simulated rain over 48 min dur-

ation ranging from pH 5.6 (no acid added) to pH 3.0 (most acidic treatment) from early June to late September.[1] The sulfate to nitrate ratio of the simulated rain was 3.1 : 1 on an equivalent basis, and the total amount of simulant added was 31.6 and 32.1 cm in 1983 and 1984, respectively.

A cultivar split plot consisted of three plant rows 3.05 m in length (0.51 m row spacing) that were end-trimmed to a 2.44 m harvest length at maturity. The distance between plants within rows was approximately 30.5 cm. All yield component data were collected from the centermost rows.[1]

Although the corn was overplanted and thinned in an attempt to achieve the desired population density of about 64,600 plants/ha, the actual plant population density for each split plot was measured in each of the 2 years from plant counts taken at harvest. The number of barren plants, ears and nubbins were counted at harvest. An ear was defined as a cob that contained over 200 kernels, whereas a nubbin was defined as a cob having between one and 200 kernels.

Stover is defined as the aboveground portion of the plant minus cob and kernels. Kernels per ear were determined by multiplying the number of rows by the number of kernels in a row. If the number of kernels per ear was determined to be less than 200, individual kernels were counted. The average number of kernels per ear was determined by summing all the kernels of the ears (cobs with greater than 200 kernels) in each split plot and dividing by the number of ears.

Height from the ground to the top of the collar of the highest exposed leaf was measured in mid-July and mid-August for both years. Four plants per harvest row were measured, and the average of those values is reported.

The two harvest rows were harvested independently and a moisture content for the grain in each row was determined with a calibrated electronic moisture meter (Burrows Moisture Meter, Evanston, IL). Grain yield from each harvest row was adjusted to a 15.5% moisture content.

The 100-seed dry weight was determined from the average of 200 kernels from each harvest row. To assess the effect of acid rain on grain quality seed oil and protein content were determined by the method of Hymowitz and co-workers[5] using a near-infrared light reflectance instrument (Dickey-John Corporation, Auburn, IL).

Analysis of variance (ANOVA) procedures were applied to data for each year as well as for the 2-year data combined. When appropriate, error 'A' and error 'B' of the split plot design were pooled to gain precision in testing main effects of pH.[2] Four contrasts testing trends and treatment extremes were determined: (1) pH linear, (2) pH quadratic, (3) pH 3.0 vs the average of the other five treatments, and (4) pH 5.6 vs the average of the other five treatments.

RESULTS AND DISCUSSION

Cultivar and year differences

Growth and yield parameters for B73 × Mo17 and Pioneer 3377 are listed in Tables 1–6. The 1983 growing season was considerably different from the 1984 growing season. In 1983 the average daily maximum and minimum temperatures from 1 July to 31 August were 31.7° and 20.2°C, whereas in 1984 they were 29.2° and 16.9°C, respectively. Average daily pan evaporation rates for those same time periods were 0.57 cm and 0.50 cm, respectively. During the 2-week period surrounding corn silking, average daily pan evaporation rate and maximum and minimum temperatures in 1983 were 0.64 cm, 34.2° and 22.9°C, whereas in 1984 they were 0.43 cm, 28.4° and 16.8°C, respectively (personal communication, Doug Jones, IL State Water Survey). These differences between growing seasons may account for some of the differences observed in growth parameters between the two growing seasons.

Averaged over both cultivars, the 1983 growing season resulted in significantly ($\alpha < 0.05$) less grain yield, fewer ears, more barren plants, taller plants, less 100-seed dry weight, and more oil and protein in seed than the 1984 growing season.

Averaged over both years there were cultivar differences in that B73 × Mo17 had significantly ($\alpha < 0.05$) less grain yield, fewer ears, fewer kernels per ear, more barren plants, more nubbins, less cob dry weight, less stover dry weight, taller plants at silking, and less oil and more protein in the seed than Pioneer 3377. The cultivar effect was not significant for either 100-seed dry weight or plant height at maturity.

Table 1. *Growth parameters of* B73 × Mo17 *corn exposed to simulated rain,* 1983

pH	Plants	Barren plants	Ears	Nubbins	Cob wt	Stover wt	Kernels per ear	Height as of 7–12	Height as of 8–10	Dry wt of 100 seeds	Seed analysis Oil	Seed analysis Protein
		(per hectare)				(kg/ha)		(m)		(g)	(%)	
5.6	63,900	2690	53,480	7740	1375	7777	651	1.78	2.65	29.56	4.78	10.74
4.6	64,260	4040	56,170	3700	1371	7670	652	1.79	2.63	28.99	4.84	10.83
4.2	63,570	7060	51,130	5720	1284	7832	670	1.78	2.63	28.96	4.74	10.80
3.8	64,580	4040	54,830	5720	1375	7716	657	1.80	2.66	29.47	4.87	10.61
3.4	62,890	3700	53,820	5380	1385	7266	669	1.78	2.63	28.82	4.68	10.49
3.0	64,260	6050	51,460	6730	1250	7642	630	1.79	2.64	29.19	4.83	10.98
Contrast*						Level of significance						
pH1	0.82	0.08	0.35	0.61	0.16	0.26	0.67	0.76	0.65	0.36	0.93	1.00
pHq	0.95	0.38	0.27	0.03	0.50	0.77	0.07	0.87	0.56	0.40	0.82	0.57
3vR	0.52	0.12	0.11	0.36	0.02	0.96	0.02	0.83	0.87	0.94	0.27	0.14
CvR	1.00	0.04	1.00	0.05	0.35	0.50	0.70	0.75	0.42	0.18	0.73	1.00

* Contrast refers to the statistical trend tested: pH1 = pH linear, pHq = pH quadratic, 3vR = pH 3.0 vs the average of the other five treatments, CvR = pH 5.6 vs the average of the other five treatments. Numerical values refer to the probability level at which significance occurs.

Table 2. *Growth parameters of* B73 × Mo17 *corn exposed to simulated rain,* 1984

pH	Plants	Barren plants	Ears	Nubbins	Cob wt	Stover wt	Kernels per ear	Height as of 7–12	Height as of 8–10	Dry wt of 100 seeds	Seed analysis Oil	Seed analysis Protein
		(per hectare)				(kg/ha)		(m)		(g)	(%)	
5.6	65,920	1340	61,230	3700	1692	8655	675	1.55	2.49	31.83	4.30	9.35
4.6	65,590	3360	58,210	4040	1649	8472	681	1.49	2.54	31.82	4.36	9.34
4.2	64,260	1340	59,860	3030	1681	8606	689	1.60	2.53	31.63	4.32	9.26
3.8	66,920	1680	58,850	6390	1679	8795	665	1.51	2.53	32.20	4.32	9.50
3.4	66,920	2020	58,530	6390	1671	8417	668	1.54	2.52	31.73	4.26	9.46
3.0	63,900	2350	56,830	5050	1627	8703	666	1.48	2.54	32.62	4.28	9.73
Contrast*						Level of significance						
pH1	0.72	0.71	0.07	0.16	0.49	0.96	0.36	0.07	0.29	0.12	0.65	0.06
pHq	0.66	0.73	0.97	0.87	0.81	0.78	0.35	0.38	0.52	0.15	0.50	0.14
3vR	0.11	0.68	0.14	0.82	0.36	0.68	0.44	0.32	0.51	0.04	0.70	0.05
CvR	0.75	0.41	0.10	0.40	0.55	0.84	0.94	0.44	0.20	0.59	0.90	0.47

* Contrast refers to the statistical trend tested: pH1 = pH linear, pHq = pH quadratic, 3vR = pH 3.0 vs the average of the other five treatments, CvR = pH 5.6 vs the average of the other five treatments. Numerical values refer to the probability level at which significance occurs.

Table 3. Growth parameters of B73 × Mo17 *corn exposed to simulated rain, 1983 and 1984 combined data*

pH	Plants	Barren plants (per hectare)	Ears	Nubbins	Cob wt	Stover wt (kg/ha)	Kernels per ear	Height as of 7–12 (m)	Height as of 8–10 (m)	Dry wt of 100 seeds (g)	Seed analysis Oil (%)	Seed analysis Protein (%)
5.6	64,910	2020	57,360	5720	1534	8216	663	1.67	2.57	30.70	4.54	10.04
4.6	64,910	3700	57,200	3870	1510	8071	667	1.64	2.59	30.40	4.60	10.09
4.2	63,900	4210	55,500	4370	1482	8219	680	1.69	2.58	30.30	4.53	10.03
3.8	63,750	2860	56,830	6050	1527	8255	661	1.65	2.59	30.83	4.59	10.05
3.4	64,910	2860	56,190	5890	1528	7842	669	1.66	2.57	30.28	4.47	9.97
3.0	64,100	4210	54,170	5890	1439	8172	648	1.63	2.59	30.90	4.56	10.36
Contrast*						Level of significance						
pH1	0.67	0.12	0.06	0.43	0.15	0.53	0.35	0.43	0.56	0.71	0.66	0.24
pHq	0.67	0.37	0.45	0.14	0.53	0.98	0.05	0.52	0.76	0.14	0.50	0.17
3vR	0.25	0.15	0.04	0.47	0.02	0.79	0.03	0.25	0.53	0.11	0.84	0.02
CvR	0.77	0.04	0.24	0.60	0.29	0.58	0.82	0.64	0.45	0.52	0.79	0.65

* Contrast refers to the statistical trend tested: pH1 = pH linear, pHq = pH quadratic, 3vR = pH 3.0 vs the average of the other five treatments, CvR = pH 5.6 vs the average of the other five treatments. Numerical values refer to the probability level at which significance occurs.

Table 4. Growth parameters of Pioneer 3377 *corn exposed to simulated rain, 1983*

pH	Plants	Barren plants (per hectare)	Ears	Nubbins	Cob wt	Stover wt (kg/ha)	Kernels per ear	Height as of 7–12 (m)	Height as of 8–10 (m)	Dry wt of 100 seeds (g)	Seed analysis Oil (%)	Seed analysis Protein (%)
5.6	64,580	1680	61,560	1340	1827	9884	666	1.73	2.66	29.00	4.98	10.23
4.6	64,260	1340	61,890	1010	1848	10266	679	1.74	2.69	29.28	5.13	10.26
4.2	64,260	2350	59,870	2350	1811	10090	674	1.74	2.64	28.96	4.97	10.13
3.8	64,580	670	61,220	2690	1836	10139	677	1.74	2.67	28.84	5.15	10.29
3.4	63,570	1680	57,860	4370	1839	9191	703	1.72	2.66	29.06	4.90	9.98
3.0	64,260	1680	61,220	1340	1872	10473	684	1.74	2.68	28.77	4.99	10.24
Contrast*						Level of significance						
pH1	0.46	0.93	0.28	0.25	0.54	0.95	0.10	0.91	0.84	0.55	0.45	0.71
pHq	0.93	0.90	0.79	0.59	0.60	0.94	0.93	0.70	0.65	0.59	0.07	0.97
3vR	1.00	0.91	0.62	0.39	0.38	0.03	0.79	0.74	0.45	0.46	0.49	0.74
CvR	0.52	0.91	0.47	0.39	0.76	0.51	0.18	0.79	0.83	0.96	0.37	0.82

* Contrast refers to the statistical trend tested: pH1 = pH linear, pHq = pH quadratic, 3vR = pH 3.0 vs the average of the other five treatments, CvR = pH 5.6 vs the average of the other five treatments. Numerical values refer to the probability level at which significance occurs.

Table 5. Growth parameters of Pioneer 3377 corn exposed to simulated rain, 1984

pH	Plants	Barren plants (per hectare)	Ears	Nubbins	Cob wt	Stover wt (kg/ha)	Kernels per ear	Height as of 7–12 (m)	Height as of 8–10 (m)	Dry wt of 100 seeds (g)	Seed analysis Oil (%)	Seed analysis Protein (%)
5.6	65,590	1680	61,230	3360	1813	8799	669	1.48	2.55	32.32	4.59	8.45
4.6	68,620	1010	64,580	3700	1958	9466	672	1.48	2.44	32.41	4.69	8.47
4.2	66,600	2020	60,870	4040	1781	8723	648	1.54	2.49	32.24	4.66	8.35
3.8	65,270	1340	59,860	4040	1884	9129	682	1.56	2.50	32.65	4.54	8.42
3.4	68,620	2350	61,560	5720	1897	8968	668	1.43	2.49	32.98	4.64	8.58
3.0	67,930	1680	61,880	4710	1947	9566	694	1.54	2.51	32.73	4.57	8.59
Contrast*						Level of significance						
pH1	0.21	0.71	0.74	0.28	0.13	0.16	0.19	0.55	0.35	0.11	0.72	0.40
pHq	0.93	0.79	0.80	0.88	0.59	0.67	0.13	0.64	0.06	0.59	0.40	0.36
3vR	0.43	1.00	0.91	0.72	0.09	0.05	0.04	0.34	0.49	0.51	0.54	0.37
CvR	0.57	1.00	0.75	0.48	0.16	0.18	0.75	0.46	0.05	0.38	0.70	0.82

* Contrast refers to the statistical trend tested: pH1 = pH linear, pHq = pH quadratic, 3vR = pH 3.0 vs the average of the other five treatments, CvR = pH 5.6 vs the average of the other five treatments. Numerical values refer to the probability level at which significance occurs.

Table 6. Growth parameters of Pioneer 3377 corn exposed to simulated rain, 1983 and 1984 combined

pH	Plants	Barren plants (per hectare)	Ears	Nubbins	Cob wt	Stover wt (kg/ha)	Kernels per ear	Height as of 7–12 (m)	Height as of 8–10 (m)	Dry wt of 100 seeds (g)	Seed analysis Oil (%)	Seed analysis Protein (%)
5.6	65,110	1680	61,390	2350	1820	9341	667	1.60	2.61	30.66	4.79	9.34
4.6	66,440	1180	63,250	2350	1903	9866	676	1.61	2.57	30.85	4.91	9.36
4.2	65,430	2190	60,380	3200	1796	9406	661	1.64	2.57	30.60	4.81	9.24
3.8	64,910	1010	60,550	3360	1840	9634	680	1.65	2.58	30.74	4.85	9.36
3.4	66,120	2020	59,700	5050	1868	9079	686	1.57	2.57	31.02	4.77	9.28
3.0	66,120	1680	61,560	3030	1910	10,020	698	1.64	2.59	30.75	4.78	9.42
Contrast*						Level of significance						
pH1	0.43	0.87	0.35	0.12	0.13	0.29	0.04	0.59	0.54	0.41	0.51	0.82
pHq	0.97	0.78	0.99	0.84	0.45	0.79	0.33	0.55	0.06	0.58	0.08	0.55
3vR	0.47	0.93	0.66	0.81	0.06	<0.01	0.11	0.30	0.32	0.11	0.39	0.41
CvR	0.32	0.93	0.79	0.28	0.21	0.17	0.23	0.42	0.12	0.42	0.45	0.97

* Contrast refers to the statistical trend tested: pH1 = pH linear, pHq = pH quadratic, 3vR = pH 3.0 vs the average of the other five treatments, CvR = pH 5.6 vs the average of the other five treatments. Numerical values refer to the probability level at which significance occurs.

Acid rain effects on plants and yield parameters

Barren plants/ha. The number of barren plants/ha for Pioneer 3377 was unaffected by treatment pH (Tables 4–6). However, for B73 × Mo17 there was a linear trend toward increasing numbers of barren plants as the acidity of the pH treatment increased, and this trend was significant ($\alpha = 0.08$) in 1983 (Table 1). Averaged over both years (Table 3) comparison of the barren plants at pH 5.6 (2020 plants/ha) with the average number of barren plants for the other five treatments (3570 plants/ha) was significantly ($\alpha = 0.04$) fewer. Although no treatment resulted in more than 7500 barren plants/ha, there were more than 70% fewer barren plants at pH 5.6 than the average of the other five treatments.

Ears/ha. The number of ears/ha for Pioneer 3377 was unaffected by treatment pH, whereas for B73 × Mo17 (Table 3) the pH linear effect over both years was significant ($\alpha = 0.06$), indicating there was a decreasing number of ears/ha as acidity of pH treatment increased. In addition, for B73 × Mo17 the number of ears at pH 3.0 (54,170 ears/ha) was significantly less than the average number of ears for the other five treatments (56,620 ears/ha). These data are consistent with the trend observed for barren plants.

Nubbins/ha. A quadratic effect of treatment pH on the number of nubbins was observed for B73 × Mo17 in 1983, but not in 1984 or for the 2-years data combined (Tables 1–3). No obvious explanation is offered for slightly more nubbins recorded at the two pH extremes for one year.

Ears plus nubbins/ha. Because the response for ears was somewhat different than that for nubbins, the effect of simulated rain acidity on the two combined (ears plus nubbins) was also analyzed (data not shown). As expected there was no trend for Pioneer 3377 over the acidity levels tested but for B73 × Mo17 the contrasts indicated the control (pH 5.6) has slightly more ears plus nubbins ($\alpha = 0.05$) than the average of the other five treatments (63,050 and 61,180, respectively) and the most acidic treatment (pH 3.0) had slightly fewer ears plus nubbins ($\alpha = 0.07$) than the average of the other five treatments (60,060 vs 61,780, respectively). These results are similar to those for ears alone since the number of nubbins observed was rather low ($< 10\%$ of the ears in most cases). These results also support the conclusion that the lower yield at the most acidic treatment was not a result of poorly filled ears only but also of nubbins and barren plants.

Cob dry weight. While there was a trend toward decreasing cob dry weight with increasing treatment acidity for B73 × Mo17, the opposite was true for Pioneer 3377 (see linear contrast for combined data in Tables 3 and 6). The cob dry weight over both years for B73 × Mo17 at pH 3.0 was significantly lower ($\alpha = 0.02$) than the average of the other five treatments (1439 and 1516 kg/ha, respectively). The same contrast for Pioneer 3377 was significant ($\alpha = 0.06$), but cob dry weight at pH 3.0 was higher than the average of the other five treatments (1910 and 1850 kg/ha, respectively). For B73 × Mo17 cob weight at pH 3.0 was significantly lower in 1983 when yield was also lower (Table 1). For Pioneer 3377, however, cob weight was slightly higher in 1984 only (Table 5).

Stover dry weight. For Pioneer 3377 in both 1983 and 1984 stover dry weight of the pH 3.0 treatment was significantly larger ($\alpha = 0.03$ and 0.05, respectively) than the average of the other five treatments. In 1983 and 1984 stover dry weight (in kg/ha) for Pioneer 3377 at the pH 3.0 treatment was 10,473 and 9566, compared to 9914 and 9017 for the average of the other five treatments for the same years, respectively. A similar trend, while not statistically significant, was observed for grain yield for this cultivar. Stover dry weight was unaffected by the level of acidity for B73 × Mo17. As expected the results for cobs plus stover (total dry matter production excluding grain) were similar to those for stover dry weight alone since the weight of cobs was approximately one-fifth the weight of dry stover.

Kernels per ear. Number of kernels per ear for Pioneer 3377 showed a significant ($\alpha = 0.04$) pH linear trend over both years and indicated that as the acidity of the pH treatment increased there was an increase in the number of kernels per ear. For B73 × Mo17 there was a significant ($\alpha = 0.05$) pH quadratic effect, and the comparison of the number of kernels per ear at pH 3.0 (648) contrasted with the average kernels per ear for the other five treatments (668) was significant ($\alpha = 0.03$). This parameter was affected more during the 1983 growing season than during the 1984 growing season.

Plant height. None of the effects tested were sig-

nificant for plant height in July. By mid-August 1984, Pioneer 3377 showed a quadratic trend ($\alpha = 0.06$) with increasing acidity, and the pH 5.6 treatment was taller than the average of the other five treatments. No effect of acidity on plant height was observed in 1983 or for B73 × Mo17.

Grain yield. Yield for B73 × Mo17 at the pH 3.0 treatment (11,765 kg/ha) was significantly less ($\alpha = 0.03$) than average yield of the other five treatments (12,441 kg/ha), whereas the pH 3.0 yield for Pioneer 3377 (13,910 kg/ha) tended to be more ($\alpha = 0.11$) than the average yield of the other five treatments (13,414 kg/ha). The yield reduction for B73 × Mo17 at pH 3.0 was greater in 1983 than in 1984. Effects on grain yield were discussed in detail by BANWART *et al.*[1]

100-seed dry weight. The different pH treatments did not significantly affect the 100-seed dry weight for Pioneer 3377. The 100-seed dry weight at pH 3.0 for B73 × Mo17 tended to be greater ($\alpha = 0.11$) than the average of the other five pH treatments, especially in 1984. The slightly larger seed size was probably due to fewer kernels per ear but did not compensate enough to prevent a somewhat lower grain yield.

Seed oil content. For Pioneer 3377 over both years there was a quadratic effect ($\alpha = 0.08$) of pH upon seed oil content (Table 6). The main effect was in 1983 (Table 4) but the maximum range observed in oil content for the treatment means was only 0.25% (Tables 3–6). Seed oil content for B73 × Mo17 was not significantly affected by treatment acidity.

Seed protein content. The seed protein content for B73 × Mo17 over both years at pH 3.0 was significantly ($\alpha = 0.02$) larger than the average protein content of the other five treatments. Thus the slightly lower seed yield at this pH was associated with somewhat higher protein levels. This comparison was not significant for Pioneer 3377.

The changes in yield parameters for B73 × Mo17 for the pH 3.0 treatment when compared to the average of the other five pH treatments were much greater in 1983 than in 1984. The 1983 growing season was warmer than average, especially during pollination. One can speculate that under heat stress the most acidic pH treatment may have had more of an effect on yield and yield components such as the number of ears and the number of kernels per ear for B73 × Mo17. Preliminary results from subsequent field studies support the postulate of an interaction of acid rain and drought stress for this cultivar. When adequate rainfall was applied acid rain had little effect on corn yields but where lack of rainfall reduced corn yields, acid rain resulted in additional reductions in harvested yields, at least for 1 year. One might also speculate that pH 3.0 is near a threshold value and that increased acidity would result in greater yield reductions for this cultivar. This, however, has not been tested and rainfall with pH less than 3.0 rarely occurs in nature.

It should also be noted that these studies were conducted on a highly buffered, fertile mollisol. For cultivated crops such as corn, however, adequate fertilizers and limestone are commonly applied and for such farming systems the effects of acid rain will likely be expressed in direct plant effects and not through changes in soil acidity. In addition to the fact that soils are amended for optimum production, the theoretical acidity from ammonium-containing fertilizers used for corn production is much greater than the theoretical acidity from acid rain.

DISCUSSION AND CONCLUSIONS

Rainfall treatments were chosen to include levels as low as 3.0 because rain events with this level of acidity have been recorded in east central Illinois and because a wide range in values enhances the development of a regression expression for a dose response function. The experimental design was chosen to include maximum exposure (pH 3.0 rain twice weekly from planting to harvest) of the crops to acid rain recognizing that natural exposure to rainfall events as low as 3.0 may be very rare. The results of this experiment indicate that even under the maximum exposure tested very few plant responses were noted.

There were no linear or quadratic trends with treatment pH for either cultivar for 100-seed weight, stover production, cob weight, barren plants or seed protein content. These conclusions support previous results with field corn[10] and suggest corn production is not seriously threatened by acid rain.

For Pioneer 3377 the number of kernels per ear

was increased slightly by acid rain and dry stover production was slightly higher at pH 3.0 than for the average of the other five treatments possibly in response to sulfur or nitrogen added in the rain.

For B73 × Mo17 none of the parameters analyzed showed a significant ($\alpha = 0.05$) linear effect with rainfall pH. There were fewer barren plants for the control (pH 5.6) than for the average of the other five treatments and several parameters were significant for the comparison of pH 3.0 treatments vs the average of the other five. Grain yield was approximately 6% less for this contrast[1] and the associated changes in parameters were fewer ears (5% reduction), less cob dry weight (5% reduction), fewer kernels per ear (3% reduction), and an increase (3%) in seed protein content. This leads to the conclusion that where small but significant yield reductions for corn occur the reduction appears to be the result of a combination of parameters previously listed and not simply a lack of ear initiation or reduced ear fill.

This study represents a large number of parameters measured and associated statistical tests. It should be pointed out that for any test with $\alpha = 0.05$, there is a 5% chance that the significant effect observed is in error. Thus with the large number of tests reported in these studies some could be statistically significant by chance. The significance of acid rain on B73 × Mo17 at pH 3.0, however, while relatively small is supported by several parameters changes as well as by yield.[1] Preliminary results from subsequent field studies with this hybrid (unpublished results) also indicate that under some environmental conditions, especially drought, acid rain of pH 3.0 may reduce yields and alter parameters as indicated by this study.

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GROWTH PARAMETER AND YIELD COMPONENT RESPONSE OF FIELD CORN TO SIMULATED ACID RAIN

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BANWART W. L., PORTER P. M., ZIEGLER E. L. and HASSETT J. J. Growth parameter and yield component response of field corn to simulated acid rain. ENVIRONMENTAL AND EXPERIMENTAL Botany **28,** 43–51, 1988.—Acid rain occurs in the midwest including major portions of the Corn Belt. Studies to date have suggested minimal yield response of field corn (*Zea mays* L.) to acid rain. However, small but significant reductions in yield have been shown for some cultivars under extreme conditions. To define further these yield changes this study examined the effect of simulated acid rain on parameters associated with corn yield. Cultivars 'B73 × Mo17' and 'Pioneer 3377' were shielded from ambient rain by two movable rain exclusion shelters. Six simulated rain treatments (pH 5.6, 4.6, 4.2, 3.8, 3.4, 3.0) were applied biweekly within these shelters through the use of a nozzle distribution system. For the most part growth and yield parameters were unaffected by simulated rain treatment. Analysis of 2 years of data for 100-seed dry weight, dry matter production, cob weight, barren plants and seed protein content indicated no significant trends ($\alpha \leqslant 0.05$) with treatment pH for either cultivar. However, when contrasted with all other treatments, a small yield reduction ($\alpha \leqslant 0.05$) observed at pH 3.0 for B73 × Mo17 (6%) was associated with a similar reduction in ears (5%), cob dry weight (5%), kernels per ear (3%) and slightly increased (3%) seed protein. Thus, while the only significant yield reduction was a contrast of pH 3.0 and the average of all other treatments for B73 × Mo17, this reduction appears to be the result both of slightly fewer ears and slightly less successful ear fill.

INTRODUCTION

ACID rain is a documented phenomenon over much of the eastern and midwestern U.S.A. including major portions of the Corn Belt. The mean annual pH of rainfall in east central Illinois where these studies were conducted is approximately 4.3. The value of field and sweet corn grown in the U.S.A. has exceeded $20 billion dollars in recent years.[11] There have been relatively few studies on the response of corn (*Zea mays* L.) to simulated acid rain, especially those that examine the entire plant development.

In 1979 the sweet corn cultivar 'Golden midget' was subjected to simulated acid rain and harvested before physiological maturity.[3,9] No data on grain yield were obtained but leaf injury (necrotic spots on the leaves) resulting from simulated rain at pH 3.0 was noted at harvest. The estimated fraction of the leaf area affected was 5% at this pH, while no apparent injury to leaves occurred at pH treatments 3.5, 4.0 and 5.6. Although foliage at pH 3.0 exhibited visible injury, total aboveground dry weight (stems and leaves) of these plants was larger by 13% than plants receiving the pH 5.6 treatment. No significant effect of simulated acid rain on roots was observed.

The effect of simulated acid rain on dent corn ('Pioneer 3992') was studied by LEE and coworkers.[6,7,8] The lowest yield was observed at pH 4.0 in both years, but only in 1980 was the difference in grain yield between the pH 4.0 treatment and the control treatment (pH 5.6) sig-

nificantly different. No significant differences in yield were noted between the control treatment and the pH 3.5 and 3.0 treatments. Depressed yields at pH 4.0 appeared to be due to a decrease in the number of two-eared plants in 1980, but not in 1981. However, stover production in 1981 was significantly reduced at the pH 4.0 treatment when compared to the control.

Total ear fresh weight, ear dry weight, grain dry weight and top dry weight for two early maturing cultivars, Pioneer 3992 and 'Northrup King PX39', were not significantly affected by simulated acid rain treatments at pH 3.5, 3.7, 3.9, 4.1, 4.3 and 5.4.[10] In additional experiments with Pioneer 3992, grain yield was not significantly affected by pH 4.0 simulated acid rain treatments of differing nitric : sulfuric acid ratios.[10] Similarly grain yields were not affected when simulated rain varied from event to event with the same season-long average. PLOCHER *et al.*[10] suggest that corn can be particularly sensitive to acid precipitation under some conditions, and that field tests are needed to evaluate the response of corn to controlled applications of simulated acid rain.[10]

Work by DUBAY and co-workers (personal communication, North Carolina State University) involved the development of greenhouse techniques to test 10 corn cultivars for relative sensitivity to simulated acid rain. Young plants were exposed for 1 hr to simulated rain at pH 5.5 or 2.5, then ranked for visible foliar injury. There was never greater than 5% foliar injury (percent of leaf surface brown or necrotic) to any of the cultivars receiving the most acidic treatment.

The buffering ability of corn (*Zea mays* rugosa, 'Butter and Sugar') leaf tissue was evaluated by placing sections of leaves in a simulated sulfuric acid rain solution.[4] The corn leaf tissue had little effect on the pH of the acid rain solution over the 4 hr time period that pH was monitored.

WALDRON *et al.*[12] investigated the susceptibility of the reproductive process in three corn cultivars to simulated acid rain. Their study focused on pollen viability and growth, as well as silk receptivity and kernel formation. Preliminary observations indicated that in one corn cultivar there was a reduced kernel number on ears where the silks and tassels were treated with simulated acid rain at pH 3.6 and that simulated acid rain may decrease pollen germination.

The primary objective of this study was to elicit more detailed information on responses of growth parameters and yield component responses of two corn cultivars to different acidity levels of simulated rain. The study was conducted in an area where corn is a major crop and where acid precipitation occurs naturally. The pH of rainfall in the geographic region of this study varies from as low as 3.0 to values as high as 7.0 with the mean annual pH of approximately 4.3 (personal communication, Illinois State Water Survey, 2204 Griffith Dr., Champaign, IL 61820). In an earlier paper the grain yield response of two corn cultivars to six levels of simulated acid rain ranging from pH 3.0 to 5.6 applied biweekly from planting to physiological maturity was reported.[1] To assess the effects of acidic precipitation on corn or other cropping systems it is important not only to examine yield but yield components and other plant parameters that may provide some evidence for the mechanism involved in acid rain effects. In this paper the growth parameters and yield component responses associated with the simulated rain acidity levels are reported.

MATERIALS AND METHODS

Field studies were conducted in 1983 and 1984 on a Flanagan silt loam (fine, montmorillonitic, mesic Aquic Argiudoll) using dent corn 'B73 × Mo17' (Illinois Foundation Seeds, Inc., Champaign, IL) and 'Pioneer 3377' (Pioneer Hy-Bred International, Princeton, IL). B73 × Mo17 was selected because of its relative sensitivity to drought stress and Pioneer 3377 because it is a high yielding commercial cultivar. The detailed experimental design, procedures and data analysis methods that were employed in this experiment were given in detail by BANWART *et al.*[1]

The statistical design consisted of a split plot with the main plot arranged in a randomized complete block design. The main plot and split plot variables were six simulated rain acidity levels and two cultivars, respectively. Plants were protected from ambient rain by movable rain exclusion shelters.[1] Corn was treated biweekly with 1.05 cm of simulated rain over 48 min dur-

ation ranging from pH 5.6 (no acid added) to pH 3.0 (most acidic treatment) from early June to late September.[1] The sulfate to nitrate ratio of the simulated rain was 3.1 : 1 on an equivalent basis, and the total amount of simulant added was 31.6 and 32.1 cm in 1983 and 1984, respectively.

A cultivar split plot consisted of three plant rows 3.05 m in length (0.51 m row spacing) that were end-trimmed to a 2.44 m harvest length at maturity. The distance between plants within rows was approximately 30.5 cm. All yield component data were collected from the centermost rows.[1]

Although the corn was overplanted and thinned in an attempt to achieve the desired population density of about 64,600 plants/ha, the actual plant population density for each split plot was measured in each of the 2 years from plant counts taken at harvest. The number of barren plants, ears and nubbins were counted at harvest. An ear was defined as a cob that contained over 200 kernels, whereas a nubbin was defined as a cob having between one and 200 kernels.

Stover is defined as the aboveground portion of the plant minus cob and kernels. Kernels per ear were determined by multiplying the number of rows by the number of kernels in a row. If the number of kernels per ear was determined to be less than 200, individual kernels were counted. The average number of kernels per ear was determined by summing all the kernels of the ears (cobs with greater than 200 kernels) in each split plot and dividing by the number of ears.

Height from the ground to the top of the collar of the highest exposed leaf was measured in mid-July and mid-August for both years. Four plants per harvest row were measured, and the average of those values is reported.

The two harvest rows were harvested independently and a moisture content for the grain in each row was determined with a calibrated electronic moisture meter (Burrows Moisture Meter, Evanston, IL). Grain yield from each harvest row was adjusted to a 15.5% moisture content.

The 100-seed dry weight was determined from the average of 200 kernels from each harvest row. To assess the effect of acid rain on grain quality seed oil and protein content were determined by the method of Hymowitz and co-workers[5] using a near-infrared light reflectance instrument (Dickey-John Corporation, Auburn, IL).

Analysis of variance (ANOVA) procedures were applied to data for each year as well as for the 2-year data combined. When appropriate, error 'A' and error 'B' of the split plot design were pooled to gain precision in testing main effects of pH.[2] Four contrasts testing trends and treatment extremes were determined: (1) pH linear, (2) pH quadratic, (3) pH 3.0 vs the average of the other five treatments, and (4) pH 5.6 vs the average of the other five treatments.

RESULTS AND DISCUSSION

Cultivar and year differences

Growth and yield parameters for B73 × Mo17 and Pioneer 3377 are listed in Tables 1–6. The 1983 growing season was considerably different from the 1984 growing season. In 1983 the average daily maximum and minimum temperatures from 1 July to 31 August were 31.7° and 20.2°C, whereas in 1984 they were 29.2° and 16.9°C, respectively. Average daily pan evaporation rates for those same time periods were 0.57 cm and 0.50 cm, respectively. During the 2-week period surrounding corn silking, average daily pan evaporation rate and maximum and minimum temperatures in 1983 were 0.64 cm, 34.2° and 22.9°C, whereas in 1984 they were 0.43 cm, 28.4° and 16.8°C, respectively (personal communication, Doug Jones, IL State Water Survey). These differences between growing seasons may account for some of the differences observed in growth parameters between the two growing seasons.

Averaged over both cultivars, the 1983 growing season resulted in significantly ($\alpha < 0.05$) less grain yield, fewer ears, more barren plants, taller plants, less 100-seed dry weight, and more oil and protein in seed than the 1984 growing season.

Averaged over both years there were cultivar differences in that B73 × Mo17 had significantly ($\alpha < 0.05$) less grain yield, fewer ears, fewer kernels per ear, more barren plants, more nubbins, less cob dry weight, less stover dry weight, taller plants at silking, and less oil and more protein in the seed than Pioneer 3377. The cultivar effect was not significant for either 100-seed dry weight or plant height at maturity.

Table 1. *Growth parameters of* B73 × Mo17 *corn exposed to simulated rain,* 1983

pH	Plants	Barren plants	Ears	Nubbins	Cob wt	Stover wt	Kernels per ear	Height as of 7–12	Height as of 8–10	Dry wt of 100 seeds	Seed analysis Oil	Seed analysis Protein
		(per hectare)				(kg/ha)		(m)		(g)	(%)	
5.6	63,900	2690	53,480	7740	1375	7777	651	1.78	2.65	29.56	4.78	10.74
4.6	64,260	4040	56,170	3700	1371	7670	652	1.79	2.63	28.99	4.84	10.83
4.2	63,570	7060	51,130	5720	1284	7832	670	1.78	2.63	28.96	4.74	10.80
3.8	64,580	4040	54,830	5720	1375	7716	657	1.80	2.66	29.47	4.87	10.61
3.4	62,890	3700	53,820	5380	1385	7266	669	1.78	2.63	28.82	4.68	10.49
3.0	64,260	6050	51,460	6730	1250	7642	630	1.79	2.64	29.19	4.83	10.98
Contrast*						Level of significance						
pH1	0.82	0.08	0.35	0.61	0.16	0.26	0.67	0.76	0.65	0.36	0.93	1.00
pHq	0.95	0.38	0.27	0.03	0.50	0.77	0.07	0.87	0.56	0.40	0.82	0.57
3vR	0.52	0.12	0.11	0.36	0.02	0.96	0.02	0.83	0.87	0.94	0.27	0.14
CvR	1.00	0.04	1.00	0.05	0.35	0.50	0.70	0.75	0.42	0.18	0.73	1.00

* Contrast refers to the statistical trend tested: pH1 = pH linear, pHq = pH quadratic, 3vR = pH 3.0 vs the average of the other five treatments, CvR = pH 5.6 vs the average of the other five treatments. Numerical values refer to the probability level at which significance occurs.

Table 2. *Growth parameters of* B73 × Mo17 *corn exposed to simulated rain,* 1984

pH	Plants	Barren plants	Ears	Nubbins	Cob wt	Stover wt	Kernels per ear	Height as of 7–12	Height as of 8–10	Dry wt of 100 seeds	Seed analysis Oil	Seed analysis Protein
		(per hectare)				(kg/ha)		(m)		(g)	(%)	
5.6	65,920	1340	61,230	3700	1692	8655	675	1.55	2.49	31.83	4.30	9.35
4.6	65,590	3360	58,210	4040	1649	8472	681	1.49	2.54	31.82	4.36	9.34
4.2	64,260	1340	59,860	3030	1681	8606	689	1.60	2.53	31.63	4.32	9.26
3.8	66,920	1680	58,850	6390	1679	8795	665	1.51	2.53	32.20	4.32	9.50
3.4	66,920	2020	58,530	6390	1671	8417	668	1.54	2.52	31.73	4.26	9.46
3.0	63,900	2350	56,830	5050	1627	8703	666	1.48	2.54	32.62	4.28	9.73
Contrast*						Level of significance						
pH1	0.72	0.71	0.07	0.16	0.49	0.96	0.36	0.07	0.29	0.12	0.65	0.06
pHq	0.66	0.73	0.97	0.87	0.81	0.78	0.35	0.38	0.52	0.15	0.50	0.14
3vR	0.11	0.68	0.14	0.82	0.36	0.68	0.44	0.32	0.51	0.04	0.70	0.05
CvR	0.75	0.41	0.10	0.40	0.55	0.84	0.94	0.44	0.20	0.59	0.90	0.47

* Contrast refers to the statistical trend tested: pH1 = pH linear, pHq = pH quadratic, 3vR = pH 3.0 vs the average of the other five treatments, CvR = pH 5.6 vs the average of the other five treatments. Numerical values refer to the probability level at which significance occurs.

Table 3. Growth parameters of B73 × Mo17 *corn exposed to simulated rain, 1983 and 1984 combined data*

pH	Plants	Barren plants (per hectare)	Ears	Nubbins	Cob wt	Stover wt (kg/ha)	Kernels per ear	Height as of 7–12 (m)	Height as of 8–10 (m)	Dry wt of 100 seeds (g)	Seed analysis Oil (%)	Seed analysis Protein (%)
5.6	64,910	2020	57,360	5720	1534	8216	663	1.67	2.57	30.70	4.54	10.04
4.6	64,910	3700	57,200	3870	1510	8071	667	1.64	2.59	30.40	4.60	10.09
4.2	63,900	4210	55,500	4370	1482	8219	680	1.69	2.58	30.30	4.53	10.03
3.8	63,750	2860	56,830	6050	1527	8255	661	1.65	2.59	30.83	4.59	10.05
3.4	64,910	2860	56,190	5890	1528	7842	669	1.66	2.57	30.28	4.47	9.97
3.0	64,100	4210	54,170	5890	1439	8172	648	1.63	2.59	30.90	4.56	10.36
Contrast*						Level of significance						
pH1	0.67	0.12	0.06	0.43	0.15	0.53	0.35	0.43	0.56	0.71	0.66	0.24
pHq	0.67	0.37	0.45	0.14	0.53	0.98	0.05	0.52	0.76	0.14	0.50	0.17
3vR	0.25	0.15	0.04	0.47	0.02	0.79	0.03	0.25	0.53	0.11	0.84	0.02
CvR	0.77	0.04	0.24	0.60	0.29	0.58	0.82	0.64	0.45	0.52	0.79	0.65

* Contrast refers to the statistical trend tested: pH1 = pH linear, pHq = pH quadratic, 3vR = pH 3.0 vs the average of the other five treatments, CvR = pH 5.6 vs the average of the other five treatments. Numerical values refer to the probability level at which significance occurs.

Table 4. Growth parameters of Pioneer 3377 *corn exposed to simulated rain, 1983*

pH	Plants	Barren plants (per hectare)	Ears	Nubbins	Cob wt	Stover wt (kg/ha)	Kernels per ear	Height as of 7–12 (m)	Height as of 8–10 (m)	Dry wt of 100 seeds (g)	Seed analysis Oil (%)	Seed analysis Protein (%)
5.6	64,580	1680	61,560	1340	1827	9884	666	1.73	2.66	29.00	4.98	10.23
4.6	64,260	1340	61,890	1010	1848	10266	679	1.74	2.69	29.28	5.13	10.26
4.2	64,260	2350	59,870	2350	1811	10090	674	1.74	2.64	28.96	4.97	10.13
3.8	64,580	670	61,220	2690	1836	10139	677	1.74	2.67	28.84	5.15	10.29
3.4	63,570	1680	57,860	4370	1839	9191	703	1.72	2.66	29.06	4.90	9.98
3.0	64,260	1680	61,220	1340	1872	10473	684	1.74	2.68	28.77	4.99	10.24
Contrast*						Level of significance						
pH1	0.46	0.93	0.28	0.25	0.54	0.95	0.10	0.91	0.84	0.55	0.45	0.71
pHq	0.93	0.90	0.79	0.59	0.60	0.94	0.93	0.70	0.65	0.59	0.07	0.97
3vR	1.00	0.91	0.62	0.39	0.38	0.03	0.79	0.74	0.45	0.46	0.49	0.74
CvR	0.52	0.91	0.47	0.39	0.76	0.51	0.18	0.79	0.83	0.96	0.37	0.82

* Contrast refers to the statistical trend tested: pH1 = pH linear, pHq = pH quadratic, 3vR = pH 3.0 vs the average of the other five treatments, CvR = pH 5.6 vs the average of the other five treatments. Numerical values refer to the probability level at which significance occurs.

Table 5. Growth parameters of Pioneer 3377 corn exposed to simulated rain, 1984

pH	Plants	Barren plants	Ears	Nubbins	Cob wt	Stover wt	Kernels per ear	Height as of 7–12	Height as of 8–10	Dry wt of 100 seeds	Seed analysis Oil	Seed analysis Protein
		(per hectare)				(kg/ha)		(m)		(g)	(%)	
5.6	65,590	1680	61,230	3360	1813	8799	669	1.48	2.55	32.32	4.59	8.45
4.6	68,620	1010	64,580	3700	1958	9466	672	1.48	2.44	32.41	4.69	8.47
4.2	66,600	2020	60,870	4040	1781	8723	648	1.54	2.49	32.24	4.66	8.35
3.8	65,270	1340	59,860	4040	1884	9129	682	1.56	2.50	32.65	4.54	8.42
3.4	68,620	2350	61,560	5720	1897	8968	668	1.43	2.49	32.98	4.64	8.58
3.0	67,930	1680	61,880	4710	1947	9566	694	1.54	2.51	32.73	4.57	8.59
Contrast*						Level of significance						
pH1	0.21	0.71	0.74	0.28	0.13	0.16	0.19	0.55	0.35	0.11	0.72	0.40
pHq	0.93	0.79	0.80	0.88	0.59	0.67	0.13	0.64	0.06	0.59	0.40	0.36
3vR	0.43	1.00	0.91	0.72	0.09	0.05	0.04	0.34	0.49	0.51	0.54	0.37
CvR	0.57	1.00	0.75	0.48	0.16	0.18	0.75	0.46	0.05	0.38	0.70	0.82

* Contrast refers to the statistical trend tested: pH1 = pH linear, pHq = pH quadratic, 3vR = pH 3.0 vs the average of the other five treatments, CvR = pH 5.6 vs the average of the other five treatments. Numerical values refer to the probability level at which significance occurs.

Table 6. Growth parameters of Pioneer 3377 corn exposed to simulated rain, 1983 and 1984 combined

pH	Plants	Barren plants	Ears	Nubbins	Cob wt	Stover wt	Kernels per ear	Height as of 7–12	Height as of 8–10	Dry wt of 100 seeds	Seed analysis Oil	Seed analysis Protein
		(per hectare)				(kg/ha)		(m)		(g)	(%)	
5.6	65,110	1680	61,390	2350	1820	9341	667	1.60	2.61	30.66	4.79	9.34
4.6	66,440	1180	63,250	2350	1903	9866	676	1.61	2.57	30.85	4.91	9.36
4.2	65,430	2190	60,380	3200	1796	9406	661	1.64	2.57	30.60	4.81	9.24
3.8	64,910	1010	60,550	3360	1840	9634	680	1.65	2.58	30.74	4.85	9.36
3.4	66,120	2020	59,700	5050	1868	9079	686	1.57	2.57	31.02	4.77	9.28
3.0	66,120	1680	61,560	3030	1910	10,020	698	1.64	2.59	30.75	4.78	9.42
Contrast*						Level of significance						
pH1	0.43	0.87	0.35	0.12	0.13	0.29	0.04	0.59	0.54	0.41	0.51	0.82
pHq	0.97	0.78	0.99	0.84	0.45	0.79	0.33	0.55	0.06	0.58	0.08	0.55
3vR	0.47	0.93	0.66	0.81	0.06	<0.01	0.11	0.30	0.32	0.11	0.39	0.41
CvR	0.32	0.93	0.79	0.28	0.21	0.17	0.23	0.42	0.12	0.42	0.45	0.97

* Contrast refers to the statistical trend tested: pH1 = pH linear, pHq = pH quadratic, 3vR = pH 3.0 vs the average of the other five treatments, CvR = pH 5.6 vs the average of the other five treatments. Numerical values refer to the probability level at which significance occurs.

Acid rain effects on plants and yield parameters

Barren plants/ha. The number of barren plants/ha for Pioneer 3377 was unaffected by treatment pH (Tables 4–6). However, for B73 × Mo17 there was a linear trend toward increasing numbers of barren plants as the acidity of the pH treatment increased, and this trend was significant ($\alpha = 0.08$) in 1983 (Table 1). Averaged over both years (Table 3) comparison of the barren plants at pH 5.6 (2020 plants/ha) with the average number of barren plants for the other five treatments (3570 plants/ha) was significantly ($\alpha = 0.04$) fewer. Although no treatment resulted in more than 7500 barren plants/ha, there were more than 70% fewer barren plants at pH 5.6 than the average of the other five treatments.

Ears/ha. The number of ears/ha for Pioneer 3377 was unaffected by treatment pH, whereas for B73 × Mo17 (Table 3) the pH linear effect over both years was significant ($\alpha = 0.06$), indicating there was a decreasing number of ears/ha as acidity of pH treatment increased. In addition, for B73 × Mo17 the number of ears at pH 3.0 (54,170 ears/ha) was significantly less than the average number of ears for the other five treatments (56,620 ears/ha). These data are consistent with the trend observed for barren plants.

Nubbins/ha. A quadratic effect of treatment pH on the number of nubbins was observed for B73 × Mo17 in 1983, but not in 1984 or for the 2-years data combined (Tables 1–3). No obvious explanation is offered for slightly more nubbins recorded at the two pH extremes for one year.

Ears plus nubbins/ha. Because the response for ears was somewhat different than that for nubbins, the effect of simulated rain acidity on the two combined (ears plus nubbins) was also analyzed (data not shown). As expected there was no trend for Pioneer 3377 over the acidity levels tested but for B73 × Mo17 the contrasts indicated the control (pH 5.6) has slightly more ears plus nubbins ($\alpha = 0.05$) than the average of the other five treatments (63,050 and 61,180, respectively) and the most acidic treatment (pH 3.0) had slightly fewer ears plus nubbins ($\alpha = 0.07$) than the average of the other five treatments (60,060 vs 61,780, respectively). These results are similar to those for ears alone since the number of nubbins observed was rather low (< 10% of the ears in most cases). These results also support the conclusion that the lower yield at the most acidic treatment was not a result of poorly filled ears only but also of nubbins and barren plants.

Cob dry weight. While there was a trend toward decreasing cob dry weight with increasing treatment acidity for B73 × Mo17, the opposite was true for Pioneer 3377 (see linear contrast for combined data in Tables 3 and 6). The cob dry weight over both years for B73 × Mo17 at pH 3.0 was significantly lower ($\alpha = 0.02$) than the average of the other five treatments (1439 and 1516 kg/ha, respectively). The same contrast for Pioneer 3377 was significant ($\alpha = 0.06$), but cob dry weight at pH 3.0 was higher than the average of the other five treatments (1910 and 1850 kg/ha, respectively). For B73 × Mo17 cob weight at pH 3.0 was significantly lower in 1983 when yield was also lower (Table 1). For Pioneer 3377, however, cob weight was slightly higher in 1984 only (Table 5).

Stover dry weight. For Pioneer 3377 in both 1983 and 1984 stover dry weight of the pH 3.0 treatment was significantly larger ($\alpha = 0.03$ and 0.05, respectively) than the average of the other five treatments. In 1983 and 1984 stover dry weight (in kg/ha) for Pioneer 3377 at the pH 3.0 treatment was 10,473 and 9566, compared to 9914 and 9017 for the average of the other five treatments for the same years, respectively. A similar trend, while not statistically significant, was observed for grain yield for this cultivar. Stover dry weight was unaffected by the level of acidity for B73 × Mo17. As expected the results for cobs plus stover (total dry matter production excluding grain) were similar to those for stover dry weight alone since the weight of cobs was approximately one-fifth the weight of dry stover.

Kernels per ear. Number of kernels per ear for Pioneer 3377 showed a significant ($\alpha = 0.04$) pH linear trend over both years and indicated that as the acidity of the pH treatment increased there was an increase in the number of kernels per ear. For B73 × Mo17 there was a significant ($\alpha = 0.05$) pH quadratic effect, and the comparison of the number of kernels per ear at pH 3.0 (648) contrasted with the average kernels per ear for the other five treatments (668) was significant ($\alpha = 0.03$). This parameter was affected more during the 1983 growing season than during the 1984 growing season.

Plant height. None of the effects tested were sig-

nificant for plant height in July. By mid-August 1984, Pioneer 3377 showed a quadratic trend ($\alpha = 0.06$) with increasing acidity, and the pH 5.6 treatment was taller than the average of the other five treatments. No effect of acidity on plant height was observed in 1983 or for B73 × Mo17.

Grain yield. Yield for B73 × Mo17 at the pH 3.0 treatment (11,765 kg/ha) was significantly less ($\alpha = 0.03$) than average yield of the other five treatments (12,441 kg/ha), whereas the pH 3.0 yield for Pioneer 3377 (13,910 kg/ha) tended to be more ($\alpha = 0.11$) than the average yield of the other five treatments (13,414 kg/ha). The yield reduction for B73 × Mo17 at pH 3.0 was greater in 1983 than in 1984. Effects on grain yield were discussed in detail by BANWART *et al.*[1]

100-seed dry weight. The different pH treatments did not significantly affect the 100-seed dry weight for Pioneer 3377. The 100-seed dry weight at pH 3.0 for B73 × Mo17 tended to be greater ($\alpha = 0.11$) than the average of the other five pH treatments, especially in 1984. The slightly larger seed size was probably due to fewer kernels per ear but did not compensate enough to prevent a somewhat lower grain yield.

Seed oil content. For Pioneer 3377 over both years there was a quadratic effect ($\alpha = 0.08$) of pH upon seed oil content (Table 6). The main effect was in 1983 (Table 4) but the maximum range observed in oil content for the treatment means was only 0.25% (Tables 3–6). Seed oil content for B73 × Mo17 was not significantly affected by treatment acidity.

Seed protein content. The seed protein content for B73 × Mo17 over both years at pH 3.0 was significantly ($\alpha = 0.02$) larger than the average protein content of the other five treatments. Thus the slightly lower seed yield at this pH was associated with somewhat higher protein levels. This comparison was not significant for Pioneer 3377.

The changes in yield parameters for B73 × Mo17 for the pH 3.0 treatment when compared to the average of the other five pH treatments were much greater in 1983 than in 1984. The 1983 growing season was warmer than average, especially during pollination. One can speculate that under heat stress the most acidic pH treatment may have had more of an effect on yield and yield components such as the number of ears and the number of kernels per ear for B73 × Mo17. Preliminary results from subsequent field studies support the postulate of an interaction of acid rain and drought stress for this cultivar. When adequate rainfall was applied acid rain had little effect on corn yields but where lack of rainfall reduced corn yields, acid rain resulted in additional reductions in harvested yields, at least for 1 year. One might also speculate that pH 3.0 is near a threshold value and that increased acidity would result in greater yield reductions for this cultivar. This, however, has not been tested and rainfall with pH less than 3.0 rarely occurs in nature.

It should also be noted that these studies were conducted on a highly buffered, fertile mollisol. For cultivated crops such as corn, however, adequate fertilizers and limestone are commonly applied and for such farming systems the effects of acid rain will likely be expressed in direct plant effects and not through changes in soil acidity. In addition to the fact that soils are amended for optimum production, the theoretical acidity from ammonium-containing fertilizers used for corn production is much greater than the theoretical acidity from acid rain.

DISCUSSION AND CONCLUSIONS

Rainfall treatments were chosen to include levels as low as 3.0 because rain events with this level of acidity have been recorded in east central Illinois and because a wide range in values enhances the development of a regression expression for a dose response function. The experimental design was chosen to include maximum exposure (pH 3.0 rain twice weekly from planting to harvest) of the crops to acid rain recognizing that natural exposure to rainfall events as low as 3.0 may be very rare. The results of this experiment indicate that even under the maximum exposure tested very few plant responses were noted.

There were no linear or quadratic trends with treatment pH for either cultivar for 100-seed weight, stover production, cob weight, barren plants or seed protein content. These conclusions support previous results with field corn[10] and suggest corn production is not seriously threatened by acid rain.

For Pioneer 3377 the number of kernels per ear

was increased slightly by acid rain and dry stover production was slightly higher at pH 3.0 than for the average of the other five treatments possibly in response to sulfur or nitrogen added in the rain.

For B73 × Mo17 none of the parameters analyzed showed a significant ($\alpha = 0.05$) linear effect with rainfall pH. There were fewer barren plants for the control (pH 5.6) than for the average of the other five treatments and several parameters were significant for the comparison of pH 3.0 treatments vs the average of the other five. Grain yield was approximately 6% less for this contrast[1] and the associated changes in parameters were fewer ears (5% reduction), less cob dry weight (5% reduction), fewer kernels per ear (3% reduction), and an increase (3%) in seed protein content. This leads to the conclusion that where small but significant yield reductions for corn occur the reduction appears to be the result of a combination of parameters previously listed and not simply a lack of ear initiation or reduced ear fill.

This study represents a large number of parameters measured and associated statistical tests. It should be pointed out that for any test with $\alpha = 0.05$, there is a 5% chance that the significant effect observed is in error. Thus with the large number of tests reported in these studies some could be statistically significant by chance. The significance of acid rain on B73 × Mo17 at pH 3.0, however, while relatively small is supported by several parameters changes as well as by yield.[1] Preliminary results from subsequent field studies with this hybrid (unpublished results) also indicate that under some environmental conditions, especially drought, acid rain of pH 3.0 may reduce yields and alter parameters as indicated by this study.

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